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FEM based simulation of the pulsed laser ablation process in nanosecond fields †

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Abstract

For the pulsed laser ablation in nanosecond fields, the key physical phenomenon of the removing process is thermal evaporation. For the process optimization of the nano-second laser ablation, it is essential to set up effective simulation that can reflect material absorption coefficient, energy intensity of laser, laser pulse shape, and so forth. In this research, material ablation in nano-second region is simulated by using a finite element method (FEM) commercial package and its result has been compared with experiment results focused on the difference in the ablation depth and its shape occurred after each laser pulse hitting. Finally, the effect of the parameter variation on the ablation process has been verified.

Keywords: Pulsed laser ablation; Finite element method; Evaporation; Nanosecond field

1. Introduction

Ablation process using a pulsed laser is widely applied in several manufacturing fields such as LCD or semiconductor industries. The pulsed laser ablation in nanosecond fields is resulted from the evaporation of heated material because electrons heated by laser hitting transfer their energy to inside electrons. Since it is similar to general heating process of a metal [1], it is possible to simulate the process based on the classic conduction theory.

On the contrary, femto-second or pico-second laser ablations are occurred caused by complicate reasons such as phase explosion, shock, and spallation [2, 3]. Usually, the laser irradiating process is completed in shorter time than the required equilibrium time between the electron and ion: therefore, clarification of femto- or pico-second laser ablation process is still unclear. As can be confirmed in Fig. 1, obvious difference of ablation area shape can be observed between nano- and femto-second laser ablation processes [4].

Through previous researches regarding the laser ablation in nanosecond fields, the process has been verified as a useful one for various materials with different laser sources. However, most previous researches for the process are based on the experimental approach rather than using numerical simulation [5-8]. Although a few papers that perform experimental research and numerical analysis simultaneously can be found [9-11], those papers are restricted to suggest limited prediction on the laser ablation or deposition result because it is hard to consider many essential parameters based on experimental results. Therefore, effective numerical simulation for the laser ablation process is inevitable.

As mentioned previously, nanosecond field laser ablation would be simulated using the classical heat conduction theory. To optimize the laser process using the nanosecond laser, it is necessary to establish a simulation method that can effectively reflects manufacturing parameters such as the absorption coefficient, the reflectivity, pulse energy and laser beam shape for various kinds of materials and lasers.

In this research, the finite element method (FEM) using the commercial package COMSOL 3.5a is used to simulate the material removal process using the nanosecond laser. While preceding researches assume that the laser works as one-dimensional heat source and a surface heating model is adopted for heat transfer analysis, this research describes two-

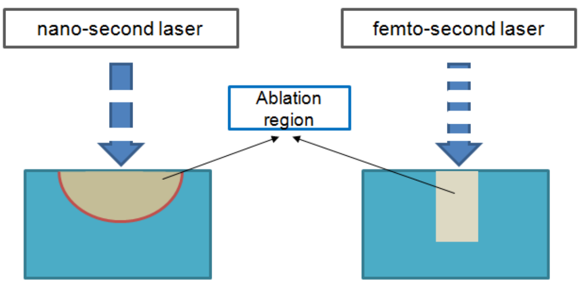

Fig. 1. Difference comparison of cross sections after nano-second and femto-second laser ablations.

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dimensional heat source that operates exterior as well as interior heat at the same time. By using the two-dimensional modeling of the laser beam without ignoring its width, the analysis can estimate the ablation efficiency, which is impossible in case of using one-dimensional modeling. Furthermore, the quantity of depth and width of the ablated portion according to different materials is also a significant factor in the simulation of the micro-fabrication field. Also, to consider differences in depth and shape of the removed material for each laser shot, variables regarding the Gauss distribution of the laser beam are taken into account.

2. Theoretical model

FEM simulation for heat conduction and heating material by a laser source is defined by a transient energy-transport equation as follows:

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = Q. \quad (1)$$

The heat source Q is represented considering the material reflectivity, the absorption coefficient of the material, laser power and the laser intensity as in Eq. (2).

$$Q = (1-R)P\alpha I \quad (2)$$

In the given system, heat generated from the laser source affects not only on the surface but also into the interior portion depending on the material absorption coefficient [12]. The laser intensity is defined by the basic law of absorption using the vertical length from the surface as in Eq. (3) [13].

$$\frac{dI}{dz} = -\alpha I \quad (3)$$

Basically, laser beam has a Gaussian distribution shape that changes according to θ defined as the degree between the material surface and the horizontal line. Due to the ablation effect, the angle changes after each shot of the laser hitting. In the case, the Gaussian distribution of the laser intensity is expressed as following:

$$I = I_p \exp\left(-x^2 \Big/ 2(\cos\theta \cdot \frac{FWHM}{2\sqrt{2\ln(2)}})^2 \right) \quad (4)$$

where FWHM is the abbreviation of the full width at half maximum with the value of 8 μm. The laser power intensity is 60 μJ and the laser intensity of peak I_p is set to 1. The distribution of the laser source is described in Fig. 2.

Using the equations described above, it is expected that the nanosecond laser ablation process can be simulated more practically because the laser heat source is defined as a two-dimensional model considering the beam width as well as its effect through depth. Even more, if an appropriate modeling in which the removed part is taken into account is adopted, differences of the ablation process at each shot of the laser hitting may be observed. Those parts are explained in section 3.

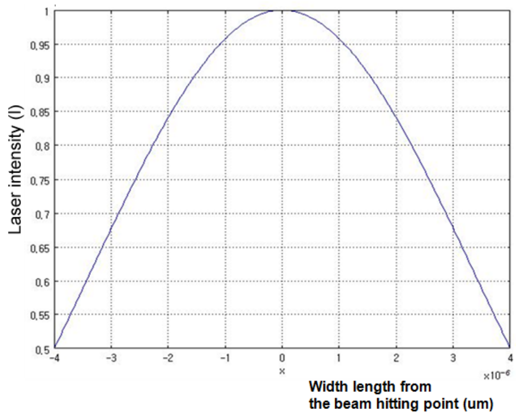


Fig. 2. Gaussian distribution of the laser intensity from the surface.

3. Modeling and result

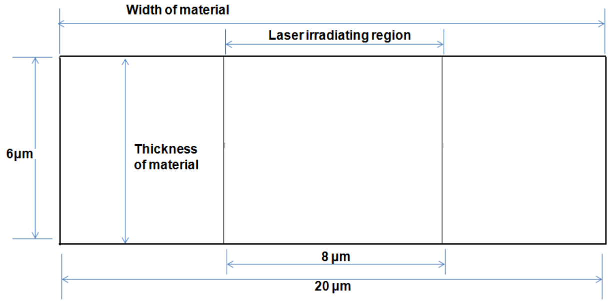
3.1 Modeling

Dimension and boundary conditions for the material are as described in Fig. 3. A laser beam with 4μm FWHM hits the surface of the material and two-dimensional modeling is adopted. The width and the thickness of the material part are set to 20 μm and 6 μm, respectively. Fig. 3(b) shows the finite element distribution and the maximum mesh size is limited to 30 *nm* which is small enough compared with the size of laser irradiation region.

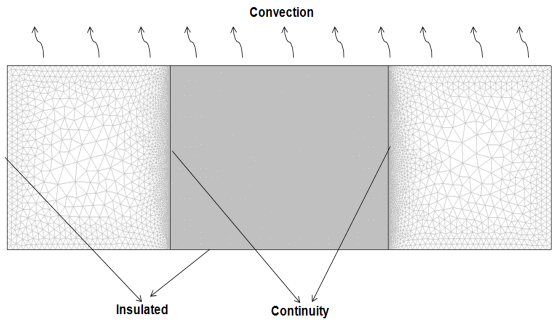
The laser irradiating region is modeled using mapped meshes to realize the material removing process and the side and the bottom parts of the material is assumed to be insulated. Therefore, the convection effect is considered only at the top surface portion. It is also assumed that there is no energy loss when the laser hits the material and flow effect of the molten material is also ignored. The FEM simulation has been performed using the commercial package COMSOL ver. 3.5a.

3.2 Simulation result and its comparison with experiments

At present, the FE commercial package that can express the floating of fluid or gas and the phase change from the solid state to gas through the fluid state due to a heat source still does not exist. Some previous works regarding the welding process use the FEM [14, 15] to represent the phase change from the solid state to fluid; however, it is hard to find a simulation result including the phase state of gas. To represent the gas state, when the material temperature exceeds its boiling point, it is assumed that the material evaporates and elements of the part would be removed. Fig. 4(a) shows the temperature distribution of a copper material after one laser shot. In accordance with the assumption, when the temperature of a part exceeds the boiling point of 2792 *K*, the portion is removed and its property changes to that of gas phase.



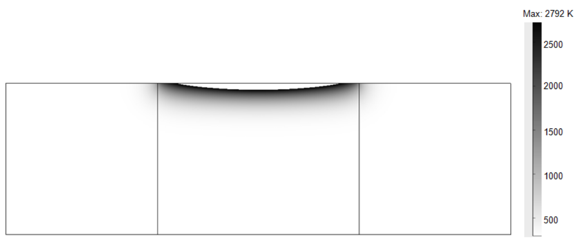
(a)



(b)

Fig. 3. Modeling for simulation : (a) material dimension; (b) boundary conditions.

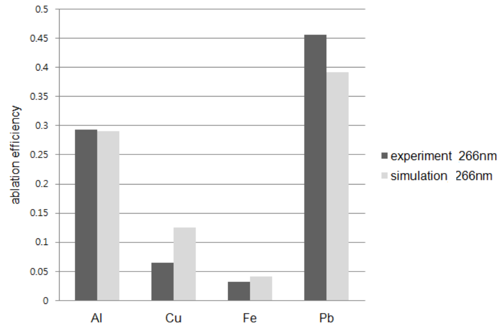
(a)



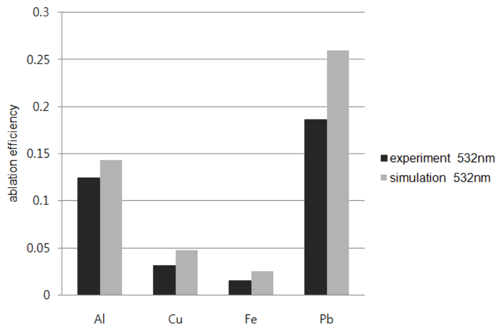
(b)

Fig. 4. Temperature distribution of Cu material : (a) after one laser shot; (b) after the ablation process.

To verify the simulation result, it is compared with experiment results given in a previous works matching boundary and load conditions as well as the material property [9]. In general, Nd-YAG laser with the wavelength of 1064 nm, 532 nm or 266 nm has been widely used in the recent experimental studies for the ablation process, 532 nm and 266 nm wavelengths are adopted to make the comparison easy. Fig. 5(a) and (b) shows comparison results for different laser wave-



(a)



(b)

Fig. 5. Simulation result comparison with experiment results for various material types : (a) 266 *nm* laser wavelength; (b) 532 *nm* laser wavelength.

length of 266nm and 532nm, respectively, in accordance with various materials. The ablation efficiency represents the removed volume of the material after one laser shot and it is expressed as the relative volume for $10^8 \mu m^3$ per the relative laser intensity of 1.0 *J*. Firstly, detail simulation conditions are selected for the aluminum material with 266nm wavelength by matching the simulation and the experiment result and the conditions are taken over to the other material cases. Although a little difference can be found in the comparison graphs, the tendency of simulation results in other cases are in consensus with the experiment results.

4. Parameter study of the ablation process

Using the simulation method established above, a parameter study for the ablation process has been performed. The laser ablation is affected and can be controlled by numerous process variables and various changes of the variables have been made to observe their effects on the efficiency of the laser ablation process.

Fig. 6 shows the tendency in which the ablation efficiency is converged as the number of shots is increased when the laser of 266nm wavelength is shot on the aluminum material. In nanosecond laser field, previous wokrs verify the convergence tendency between the number of shots and the depth or the width of the ablation portion [7, 9].

Fig. 7 shows the ablation efficieny when the laser with 266 nm wavelength is irrdiated on two materials, aluminum and

Fig. 6. Converged ablation efficiency according to the 266 *nm* laser shots on the Al material.

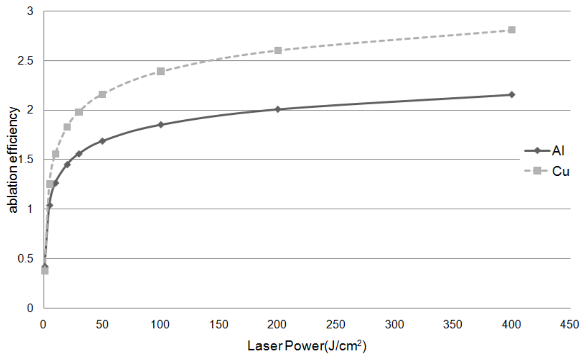


Fig. 7. Ablation efficiency of Al and Cu material by changing the laser power.

copper, by changing the laser power and the convergence tendency can be also verified. The experiment by Semerok et al. also confirms that the ablation efficiency is not proportional to the increase of the laser strength in case of laser ablation using nanosecond laser [8].

The absorption coefficient of a material varies according to the wavelength change of the laser shot and it causes the ablation efficiency change in general. However, in case of the ablation process for metal, the effect due to the absorption coefficient change is insignificant. The optical penetration depth of the laser is the reciprocal of the absorption coefficient and it becomes very small for the metal case because the metal has large absorption coefficent around 10^8 m^{-1}. Therefore, for the metal case, the ablation efficiency is affected more by the surface reflectivity rather than by the absorption coefficient value. Fig. 8 shows the simulation result of the ablation efficiency when the wavelength of the laser changes during the aluminum material ablation process. It can be confirmed that the tendency of the ablation efficiency is almost opposite to that of the material reflectivity value.

The change of ablation efficiency of the aluminum and the copper material in response to different pulse width are shown in Fig. 9. It is attempted to find the laser pulse width for the purpose of the maximum ablation efficiency for staying in the range of nanosecond field and maintaining the thermodynamic equilibrium of free electron and phonon. The laser intensity is

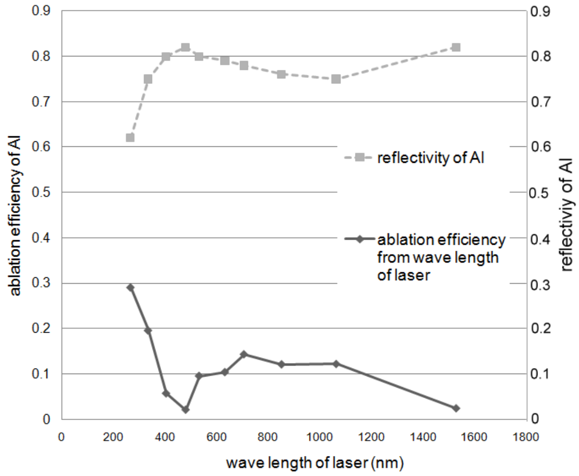


Fig. 8. Effect of Al reflectivity on the ablation efficiency.

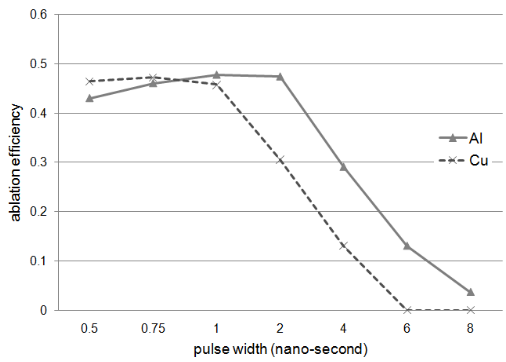


Fig. 9. Influence of the variation of the laser pulse width at Al and Cu ablation process.

set to 0.7 J/cm^2 with its wavelength of 266nm. As shown in the graph, for the case of the aluminum material, the maximum efficiency is obtained at 1~2 nanosecond pulse width while for the case of copper material, it is estimated at 0.75 nanosecond pulse width.

Using the optimal condition for the laser pulse width obtained from the result shown in Fig. 9, the ablation efficiency variation according to the number of shots on the aluminum material is observed as described in Fig. 10. Because the simulation has been performed using the maximum efficiency condition, the ablation efficiency of the first shot is higher than the case shown in Fig. 6. Although the efficiency is improved as the number of shot increases, the ablation efficiency tend to be saturated as can be confirmed in the figure and it corresponds to previous works [7, 9].

5. Conclusions

In this paper, the FEM commercial package COMSOL 3.5a is used to simulate the material removing during the laser ablation process. It is based on the assumption that the process occurs due to the material evaporation by heating of nanosecond laser shots.

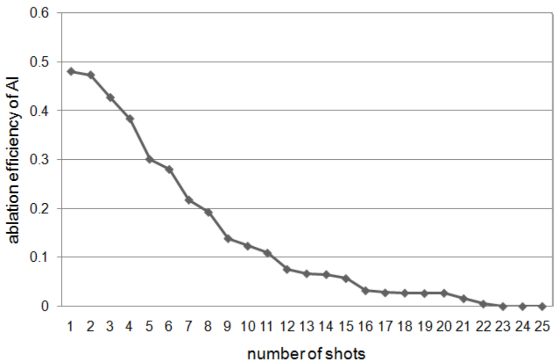


Fig. 10. Converged ablation efficiency according to the variation of shot numbers on Al material with 266 *nm* laser wavelength.

Simulation results are verified by comparison with previous experimental results. The parameter study is performed to observe the most effective condition of the ablation process. It is noteworthy that the optimal ablation condition depends on the material type, laser wavelength and its intensity, and so forth. However, it is expected that the simulation process established in this study may contribute to the improvement of the ablation process using the nanosecond pulsed laser.

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Nomenclature

ρ : Density (kg/m^3)
C_p : Heat capacity (J/(kg·K))
T : Temperature (K)
t : Time (sec)
k : Thermal conductivity (W/(m·K))
Q : Heat source (W/m)
R : Reflectivity
P : Laser power (W)
α : Absorption coefficient (m^{-1})
I : Laser intensity
z : Vertical length from the surface (m)
I_p : Laser intensity of peak
x : Horizontal length from the heat source (m)

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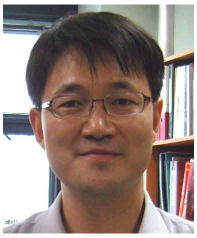

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